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Parametric Experimental Study of the Formation of Glaze Ice Shapes on Swept Wings

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Run Number	Sweep Angle	Velocity (mph)	Temperature (°F)	LWC (g/m^3)	MVD (μm)	Ice Accretion Time (min)
O33098.01	0°	150	25	0.75	20	10
O41398.01	0°	150	25	0.75	20	10
O41398.02	0°	75	25	0.75(0.80)	20	10
O41398.03	0°	100	25	0.75	20	10
O41398.04	0°	125	25	0.75	20	10
O41398.05	0°	175	25	0.75	20	10
O41398.06	0°	200	25	0.75	20	10
O41398.07	0°	225	25	0.75	20	10
O41498.18	45°	150	25	0.75	20	10 minutes
O41598.01	5°	150	25	0.75	20	10
O41598.02	10°	150	25	0.75	20	10
O41598.03	15°	150	25	0.75	20	10
O41598.04	20°	150	25	0.75	20	10
O41598.05	25°	150	25	0.75	20	10
O41598.06	30°	150	25	0.75	20	10
O41598.07	35°	150	25	0.75	20	10
O41598.08	40°	150	25	0.75	20	10
O41598.09	45°	150	25	0.75	20	10
O41698.01	5°	200	25	0.75	20	10
O41698.02	10°	200	25	0.75	20	10
O41698.03	15°	200	25	0.75	20	10
O41698.04	20°	200	25	0.75	20	10
O41698.05	25°	200	25	0.75	20	10
O41698.06	30°	200	25	0.75	20	10
O41698.07	35°	200	25	0.75	20	10
O41698.08	40°	200	25	0.75	20	10
O41698.09	45°	200	25	0.75	20	10
O41698.10	5°	100	25	0.75	20	10
O41798.01	10°	100	25	0.75	20	10
O41798.02	15°	100	25	0.75	20	10
O41798.03	20°	100	25	0.75	20	10
O41798.04	25°	100	25	0.75	20	10
O41798.05	30°	100	25	0.75	20	10
O41798.06	35°	100	25	0.75	20	10
O41798.07	40°	100	25	0.75	20	10
O41798.08	45°	100	25	0.75	20	10
O41798.09	45°	75	25	0.75(0.80)	20	10
O41798.10	40°	75	25	0.75(0.80)	20	10
O41798.11	35°	75	25	0.75(0.80)	20	10
O41798.12	30°	75	25	0.75(0.80)	20	10
O41798.13	25°	75	25	0.75(0.80)	20	10
O41798.14	20°	75	25	0.75(0.80)	20	10
O41798.15	15°	75	25	0.75(0.80)	20	10
O41798.16	10°	75	25	0.75(0.80)	20	10
O41798.17	5°	75	25	0.75(0.80)	20	10
101398.10	0°	75	25	0.75(0.80)	20	10

Table 2. Test Matrix for the icing runs at an ice accretion time of 10 minutes

Run Number	Sweep Angle	Velocity (mph)	Temperature (°F)	LWC (g/m^3)	MVD (μm)	Ice Accretion Time (min)	Critical Distance (mm)
O62096.05	15	150	25	0.75	20	2	10.1
O62196.05	15	200	25	0.75	20	10	6.8
O62196.06	15	250	25	0.75	20	10	4
O62096.01	30	150	25	0.75	20	2	6
O62196.01	30	200	25	0.75	20	10	2
O62196.02	30	250	25	0.75	20	10	0
O62196.03	45	100	25	0.75	20	10	0
O61896.04	45	150	25	0.75	20	2	0
O62196.04	45	250	25	0.75	20	10	0

Table 3. Values of the critical distance measured when the old spray system was still installed in the IRT.

Run Number	Sweep Angle	Velocity (mph)	Temperature (°F)	LWC (g/m^3)	MVD (μm)	Ice Accretion Time (min)	Critical Distance (mm)
101398.01	15	150	25	0.75	20	2	9.8 (11.0)
101398.02	15	200	25	0.75	20	10	6.5 (6.5)
101398.03	15	250	25	0.75	20	10	4.5 (4.5)
101398.04	30	150	25	0.75	20	2	6.4 (6.5)
101398.05	30	200	25	0.75	20	10	2.5 (2.5)
101398.06	30	250	25	0.75	20	10	0
101398.07	45	100	25	0.75	20	10	0
101398.08	45	150	25	0.75	20	2	0
101398.09	45	250	25	0.75	20	10	0

Table 4. Values of the critical distance measured after a new spray system was installed in the IRT.

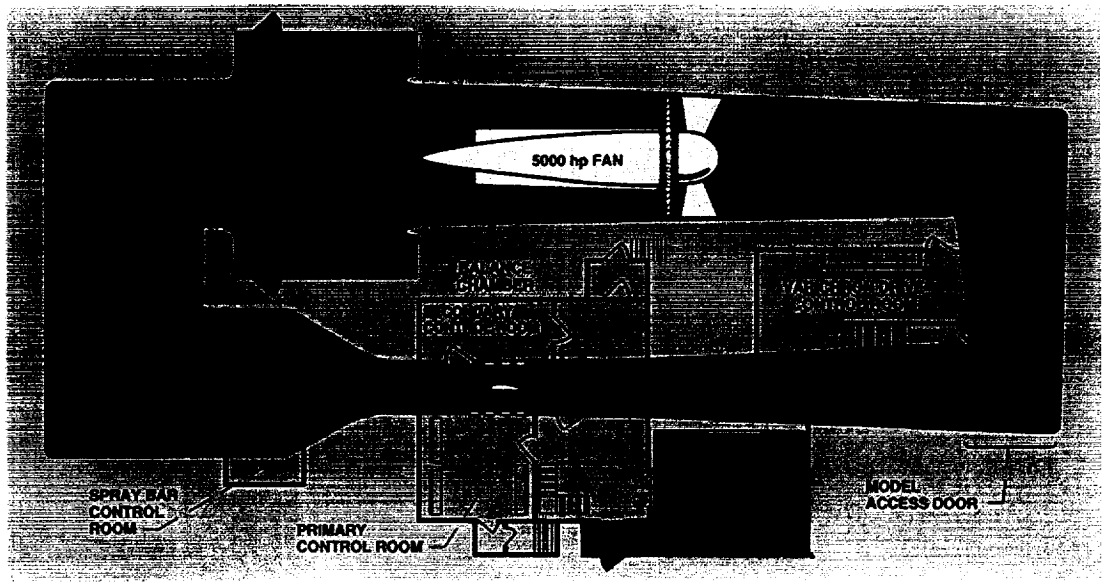


Figure 1. NASA Lewis Icing Research Tunnel, Plan view.

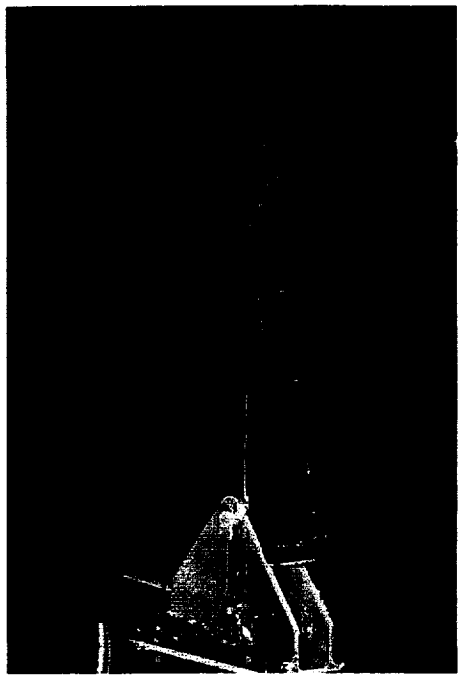


Figure 2. NACA 0012 swept wing tip in the IRT Test Section

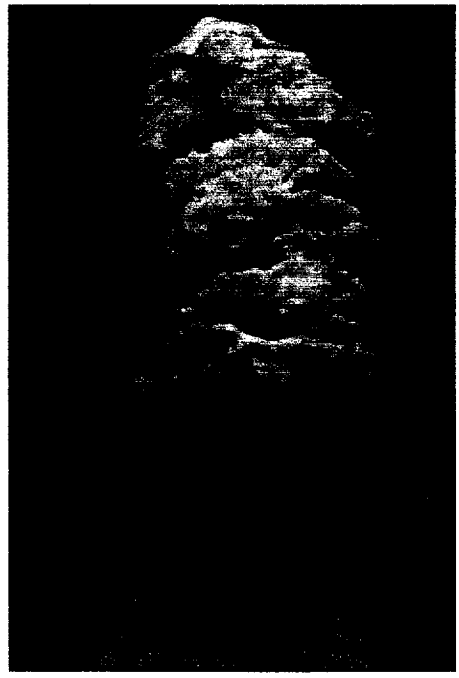


Figure 3. Urethane casting of an ice accretion.

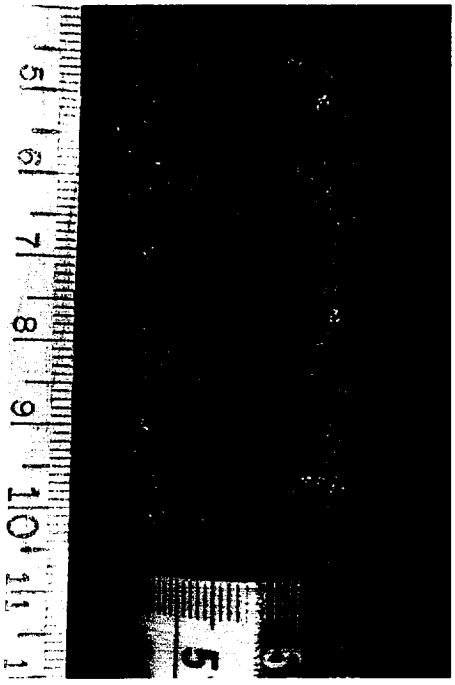


Figure 4. Front view of ice accretion at 2 minutes, showing the attachment line zone and the glaze ice feathers zone. Run conducted with 1998 spray system. Λ=15°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=2min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

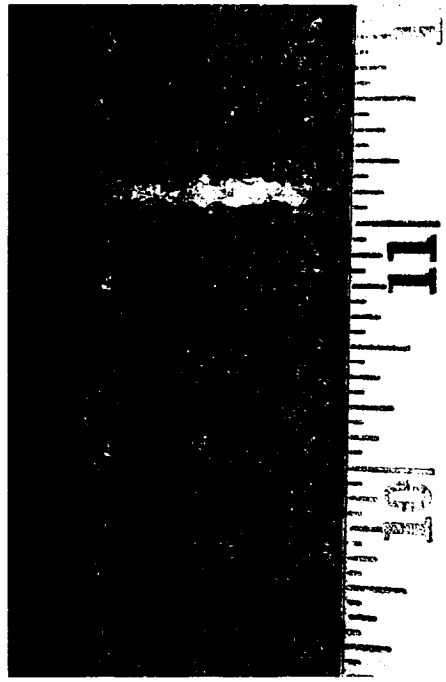


Figure 5. Front view of ice accretion at 2 minutes, showing the attachment line zone and the glaze ice feathers zone. Run conducted with 1996 spray system. Λ=15°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=2min. Direction of flow is from bottom to top, scale of ruler is in inches.

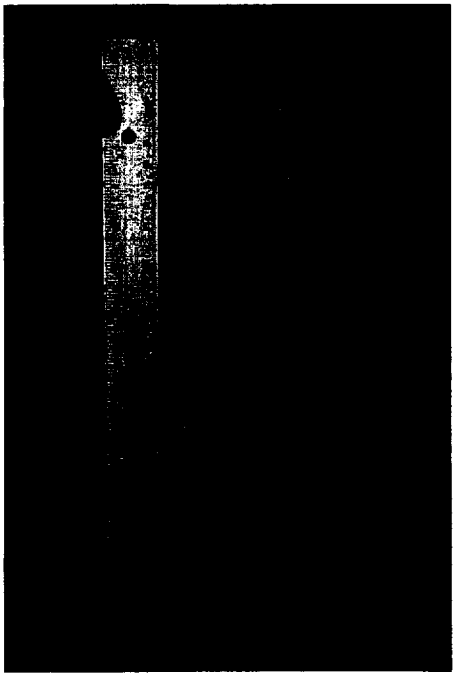


Figure 6. Front view of ice accretion. Run conducted with 1998 spray system. Λ=15°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters and inches.

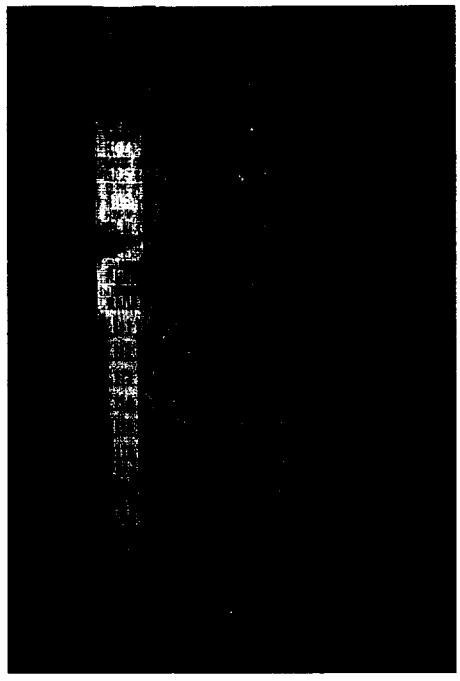


Figure 7. Front view of ice accretion. Run conducted with 1996 spray system. Λ=15°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

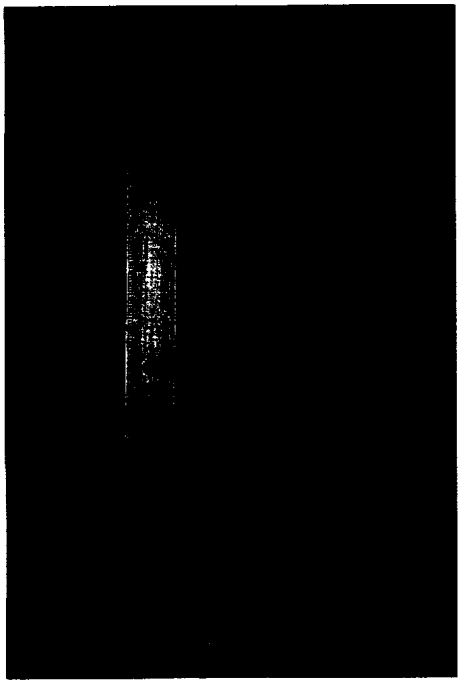


Figure 8. Front view of ice accretion. Run conducted with 1998 spray system. Λ=30°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters and inches.

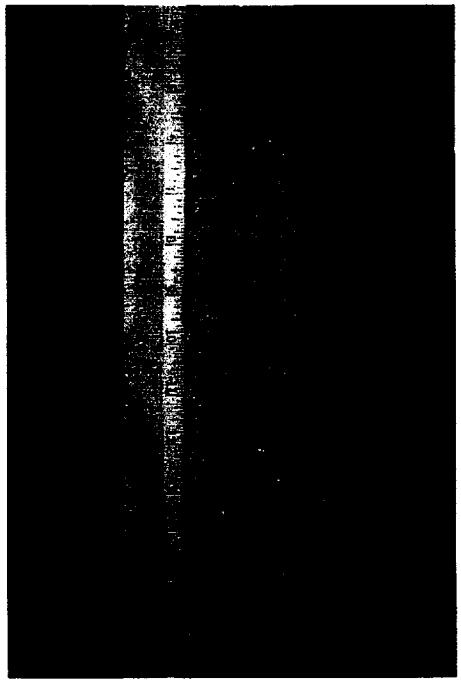


Figure 9. Front view of ice accretion. Run conducted with 1996 spray system. Λ=30°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in inches.

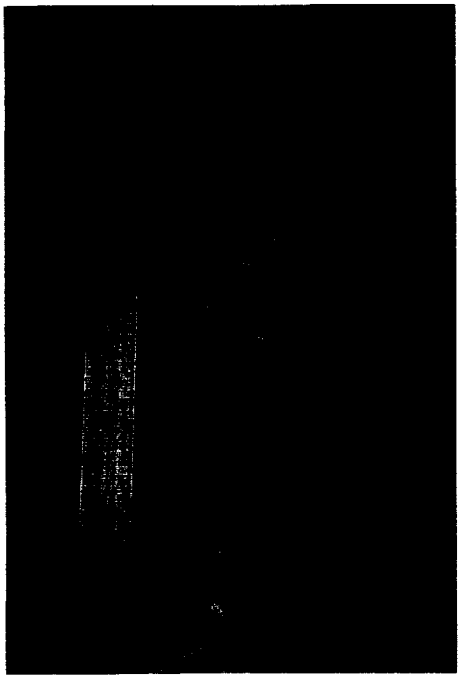


Figure 10. Front view of ice accretion. Run conducted with 1998 spray system. Λ=45°, V=250 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters and inches.

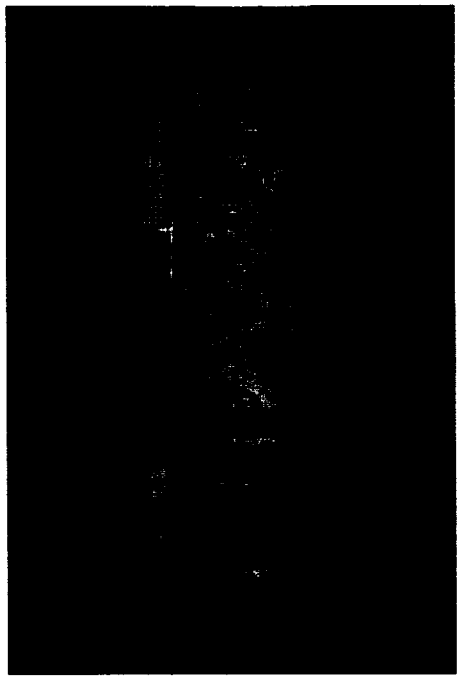


Figure 11. Front view of ice accretion. Run conducted with 1996 spray system. Λ=45°, V=250 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

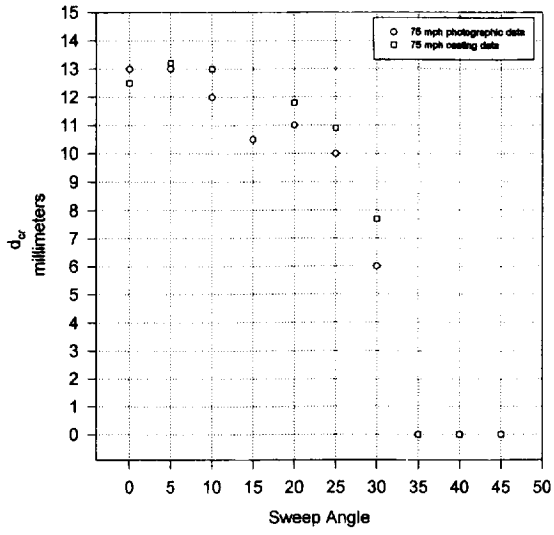


Figure 12. Change in critical distance with sweep angle at a velocity of 75 mph. Λ=0° to 45° at 5° increments, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min.

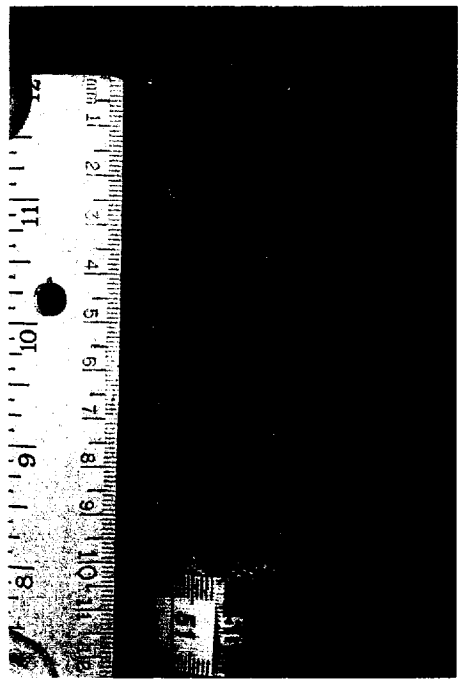


Figure 13. Front view of ice accretion, showing the attachment line zone and the glaze ice feathers zone at Λ=0°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=10min. Scale of ruler is in centimeters, smallest division 1 millimeter.

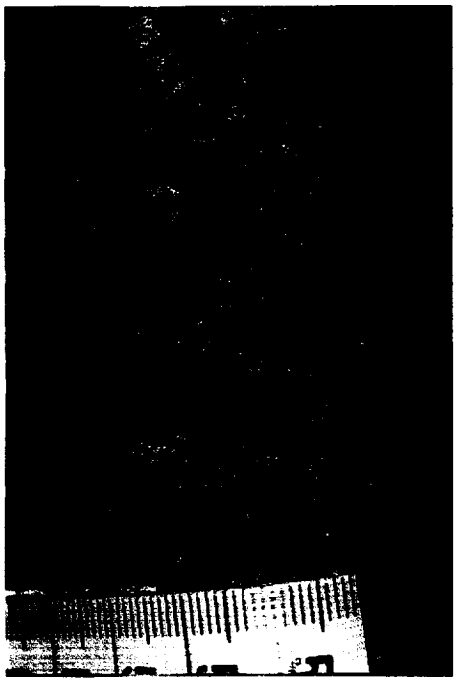


Figure 14. Side view of the glaze ice feathers zone showing the individual feathers with a preferred direction of growth. Λ=0°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=10min. Scale of ruler is in centimeters, smallest division 1 millimeter.

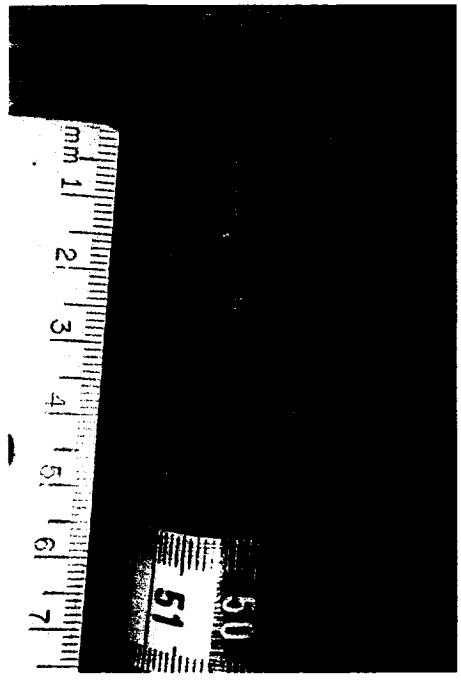


Figure 15. Front view of ice accretion showing the attachment line zone and the glaze ice feathers zone at Λ=30°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

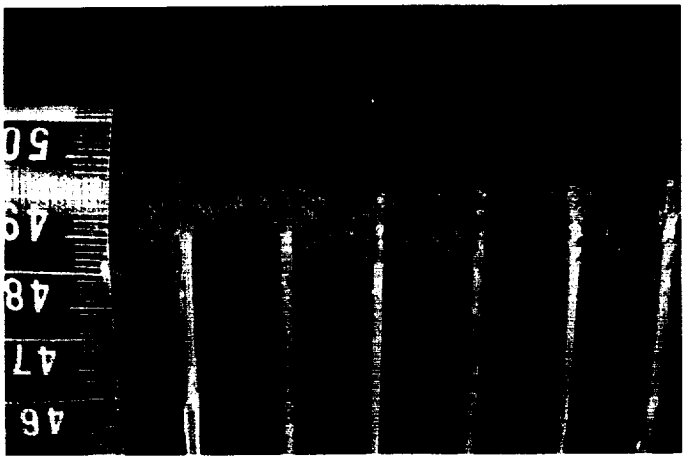


Figure 16. Side view of the ice accretion showing the glaze ice feathers zone at Λ=30°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min. Direction of flow is from left to right, scale of ruler is in centimeters, smallest division 1 millimeter.

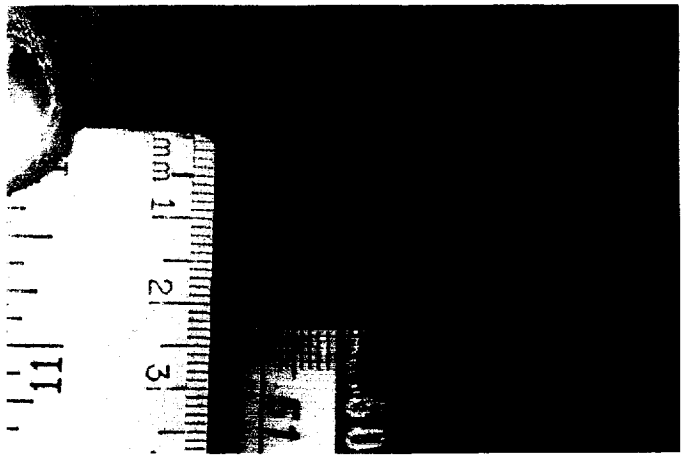


Figure 17. Front view of the ice accretion showing the top part of large feathers along the attachment line area. Λ=35°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

Figure 18. Side view of the ice accretion showing the glaze ice feathers zone and the top part of large feathers along the attachment line area. Λ=35°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min. Direction of flow is from left to right, scale of ruler is in centimeters, smallest division 1 millimeter.

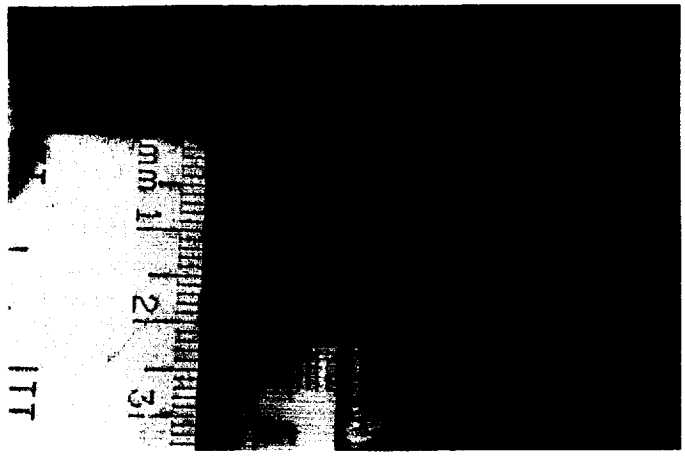


Figure 19. Front view of ice accretion showing the top of large feathers along the attachment line area. Λ=40°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division is 1 millimeter.

Figure 20. Side view of the ice accretion showing the top of large feathers along the attachment line area. Λ=40°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min. Direction of flow is from left to right, scale of ruler is in centimeters, smallest division 1 millimeter.

Figure 21. Side view of the ice accretion showing the top of large feathers along the attachment line area. Λ=45°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min. Direction of flow is from left to right, scale of ruler is in centimeters, smallest division 1 millimeter.

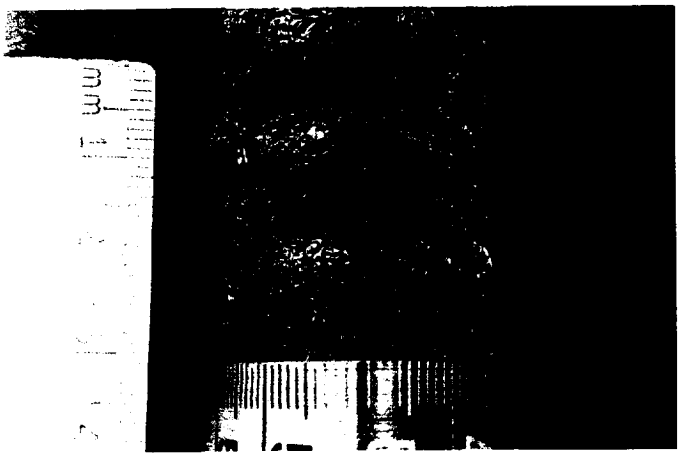


Figure 22. Front view of the ice accretion showing the attachment line zone, and the glaze ice feathers zone. The orientation of the preferred direction of growth of the feathers can be observed. Λ=10°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

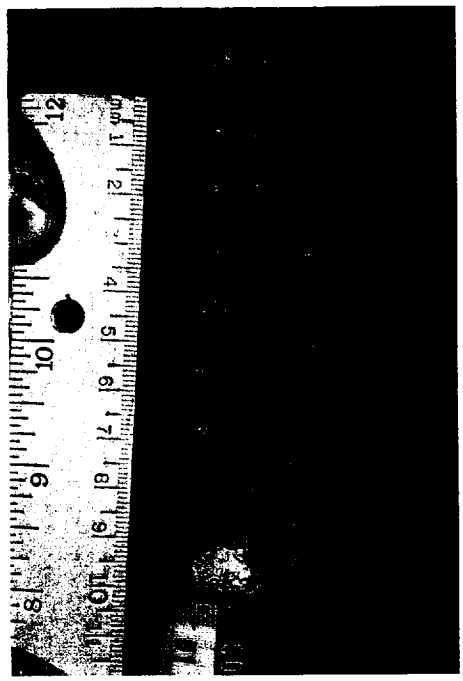


Figure 23. Front view of the ice accretion showing the orientation of the preferred direction of growth of the feathers. Λ=15°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

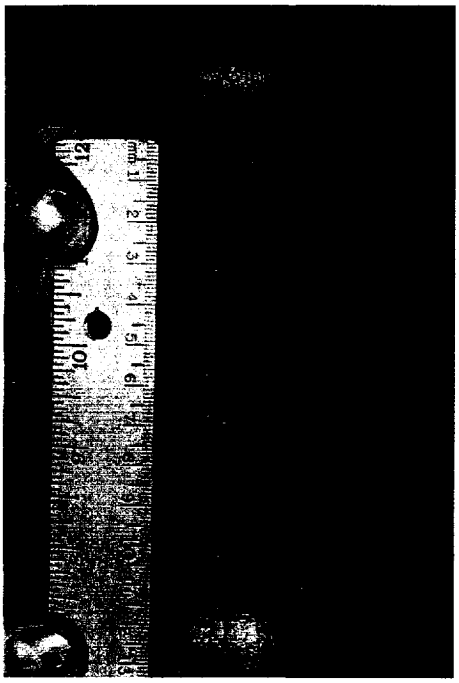


Figure 24. Front view of ice accretion showing the orientation of the preferred direction of growth of the feathers. Λ=20°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters and inches.

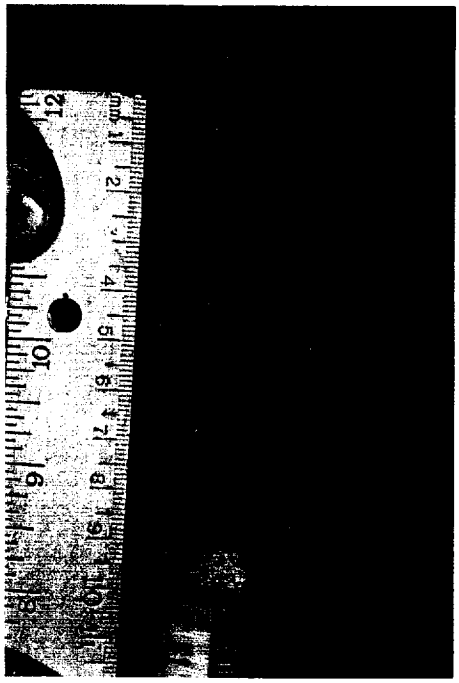


Figure 25. Front view of ice accretion showing the feathers forming scallop tips. Λ=30°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

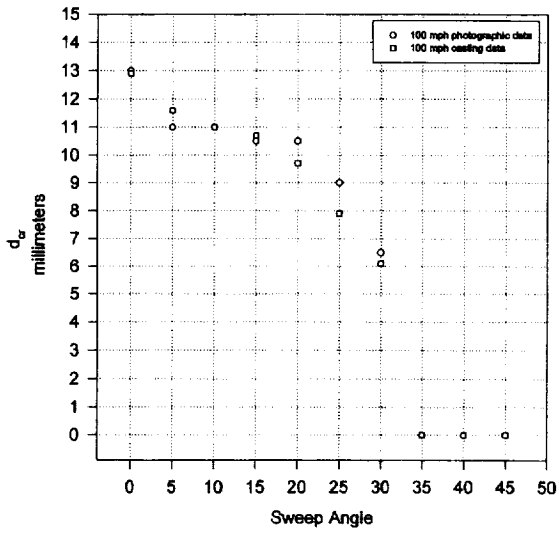


Figure 26. Change in critical distance with sweep angle at a velocity of 100 mph. Λ=0° to 45° at 5° increments, V=100 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min.

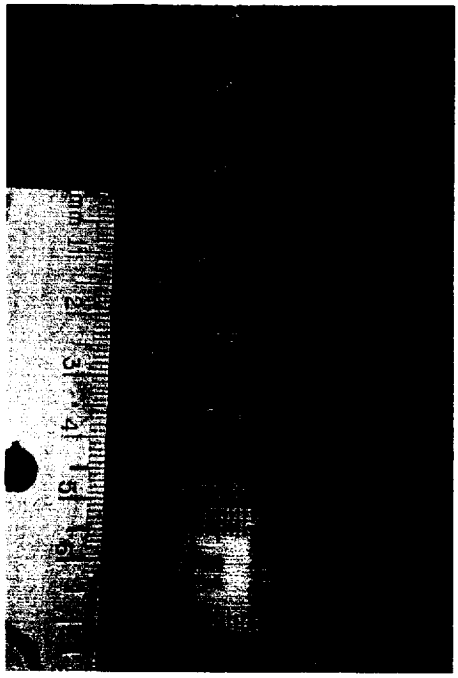


Figure 27. Front view of the ice accretion showing the attachment line zone and the glaze ice feathers zone. Λ=0°, V=100 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Scale of ruler is in centimeters, smallest division 1 millimeter.

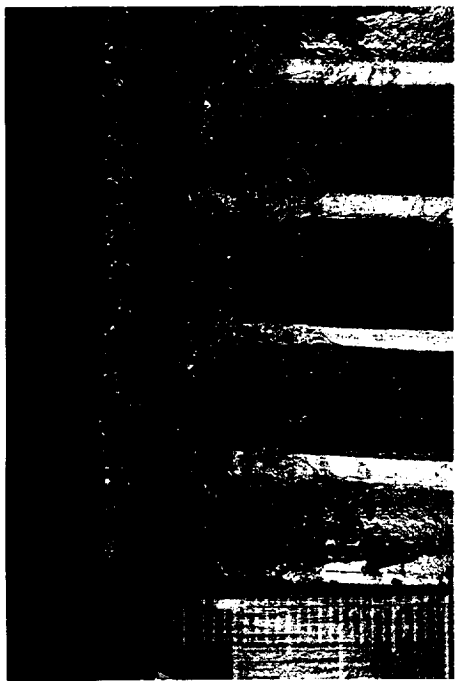


Figure 28. Side view of ice accretion showing individual feathers in the glaze ice feathers zone. Λ=0°, V=100 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Scale of ruler is in centimeters, smallest division 1millimeter.

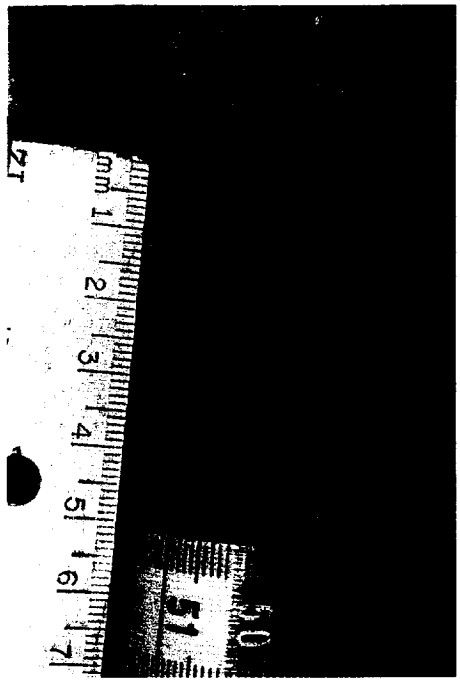


Figure 29. Front view of ice accretion showing the attachment line zone and the glaze ice feathers zone. Λ=25°, V=100 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1millimeter.

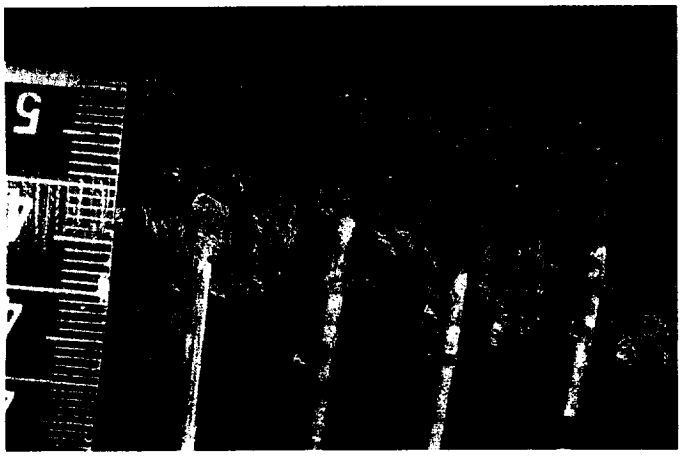


Figure 30. Side view of ice accretion showing the feathers in the glaze ice feathers zone. Λ=25°, V=100 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from left to right, scale of ruler is in centimeters, smallest division 1millimeter.

Figure 31. Side view of the ice accretion showing the top of large feathers along the attachment line area. Λ=35°, V=100 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from left to right, scale of ruler is in centimeters, smallest division 1 millimeter.

Figure 32. Side view of ice accretion showing large feathers along the attachment line area. Λ=40°, V=100 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from left to right, scale of ruler is in centimeters, smallest division 1 millimeter.

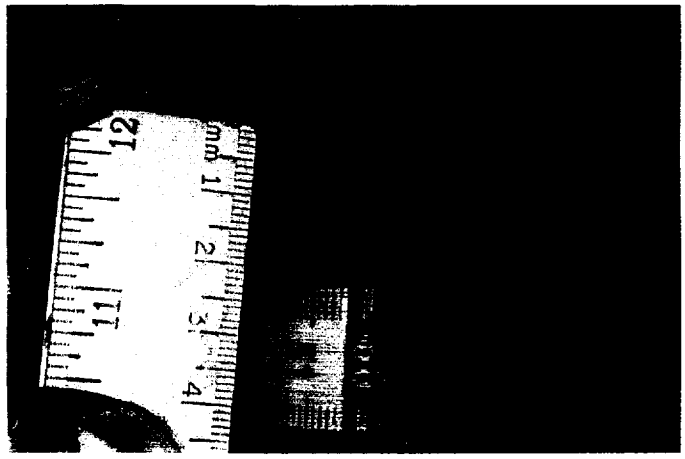


Figure 33. Complete scallop at Λ=45°, V=100 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

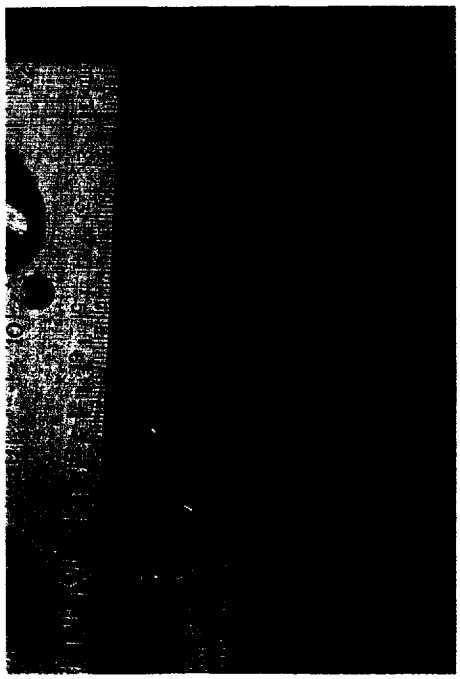


Figure 34. Front view of ice accretion showing the ice of the attachment line zone covering most of the feathers in the glaze ice feathers zone. Λ=15°, V=100 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

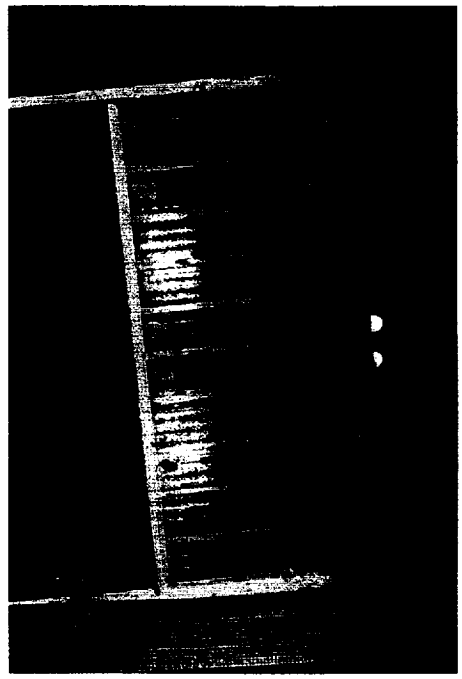


Figure 35. Side view of ice accretion showing the feathers in the glaze ice feathers zone. Λ=15°, V=100 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

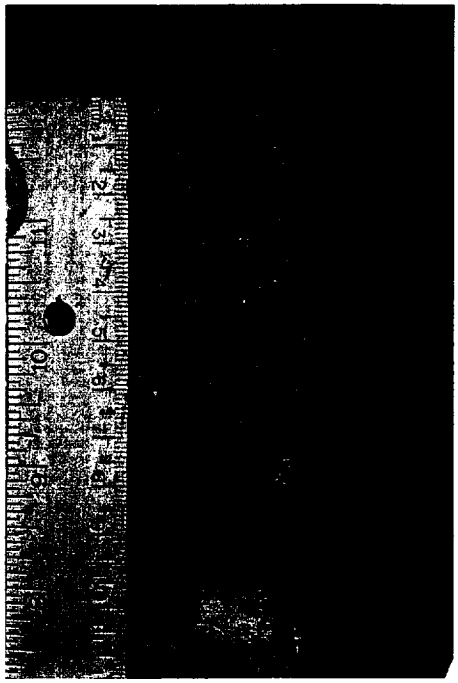


Figure 36. Front view of ice accretion showing the formation of scallop tips. Λ=25°, V=100 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=10min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

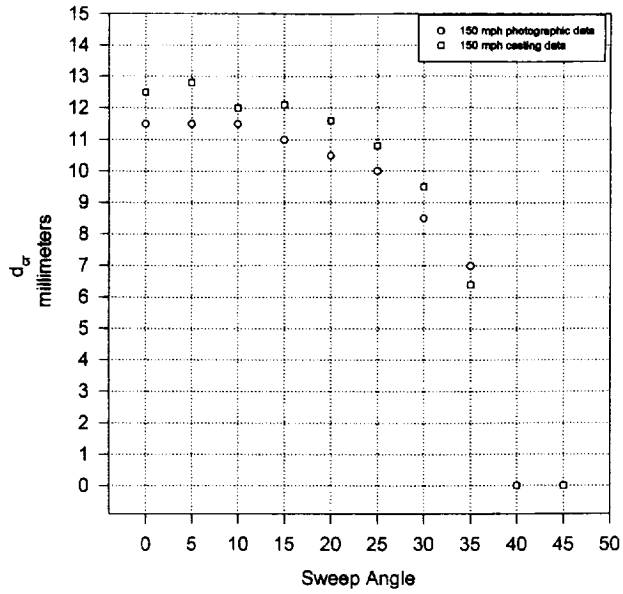
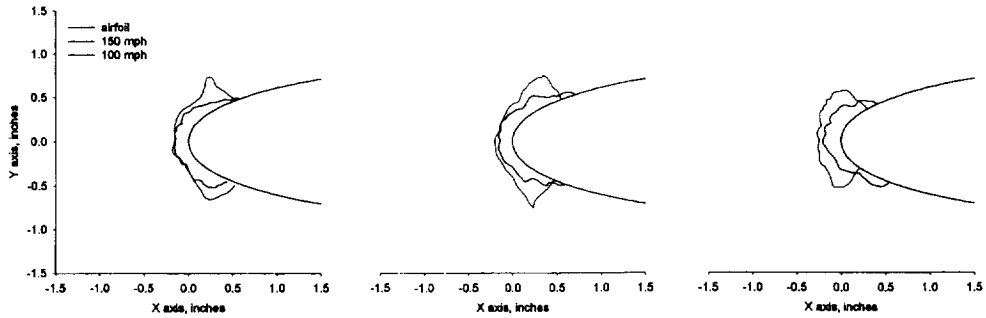


Figure 37. Change in critical distance with sweep angle at a velocity of 150 mph. Λ=0° to 45° at 5° increments, V=150 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min.



Λ = 0° Λ = 20° Λ = 40°

Figure 38. Pencil tracings of the ice shapes for sweep angles of 0°, 20°, and 40°, at velocities of 100 and 150 mph.

Figure 39. Front view of ice accretion showing the attachment line zone and the glaze ice feathers zone. Λ=0°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Scale of ruler is in centimeters, smallest division 1 millimeter.

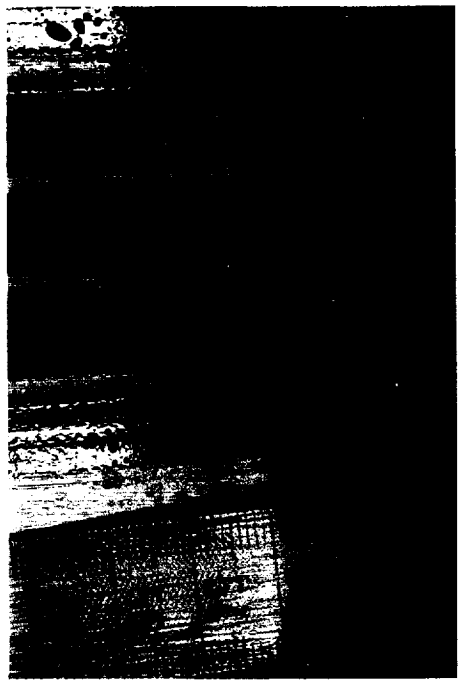


Figure 40. Side view of the ice accretion showing the ice of the attachment line zone covering the feathers in the glaze ice feathers zone. Λ=0°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Scale of ruler is in centimeters, smallest division 1 millimeter.

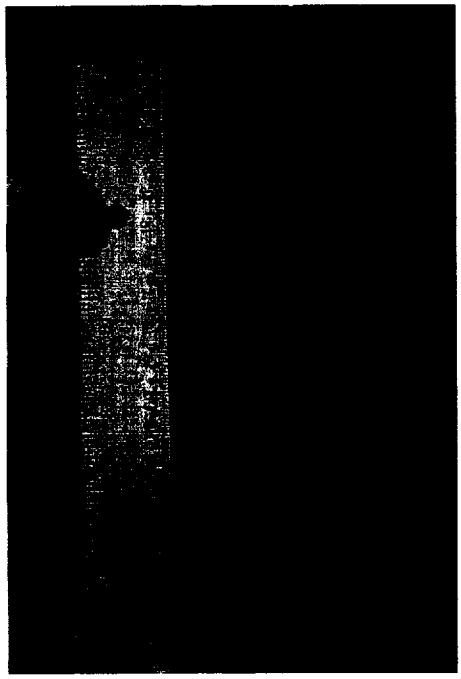


Figure 41. Front view of ice accretion showing the attachment line zone and the glaze ice feathers zone, with the feathers not forming scallop tips. Λ=10°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

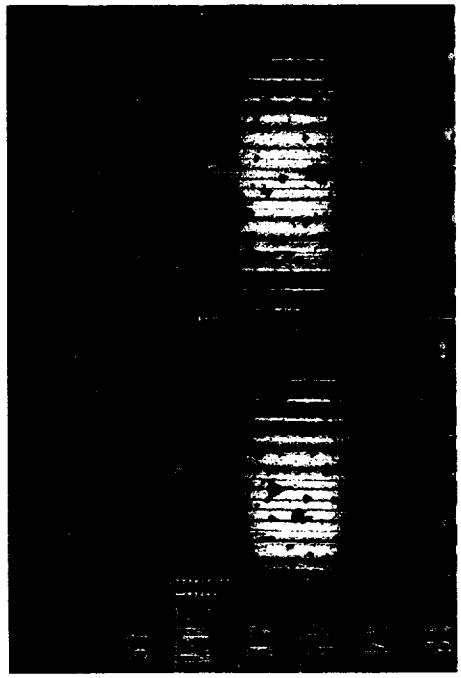


Figure 42. Side view of ice accretion showing the ice of the attachment line zone covering the feathers. Λ=10°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

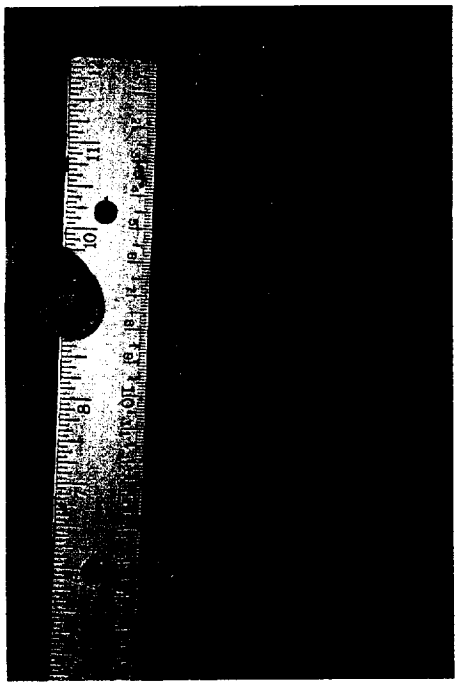


Figure 43. Front view of ice accretion showing the formation of scallop tips. Λ=25°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

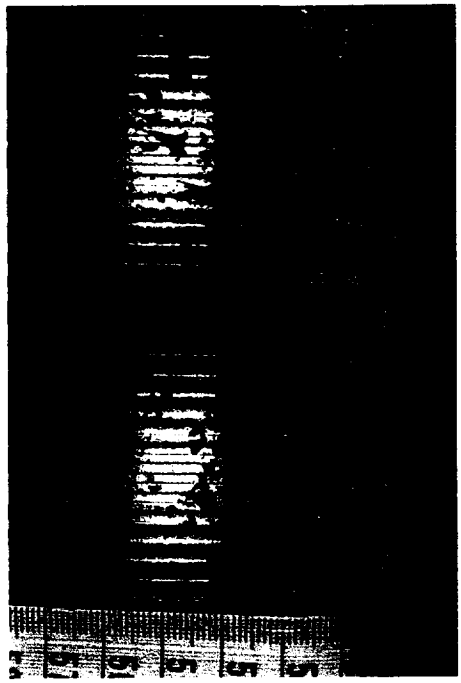


Figure 44. Side view of the ice accretion showing the feathers in the glaze ice feathers zone forming scallop tips. Λ=25°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, upper scale of ruler is in centimeters, smallest division 1 millimeter.

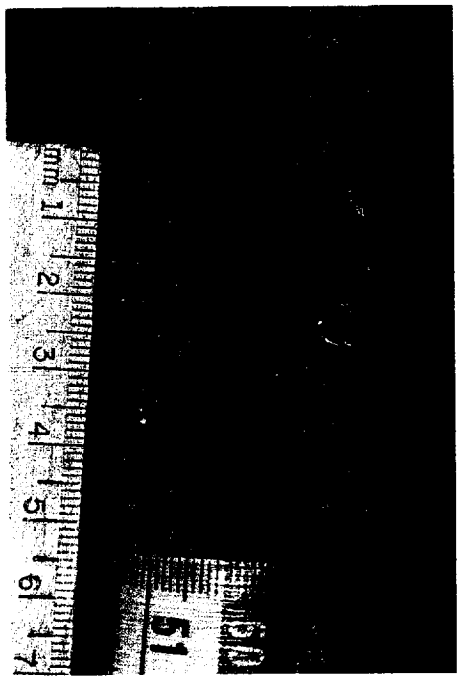


Figure 45. Front view of ice accretion showing scallop tips and the attachment line zone. Λ=35°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

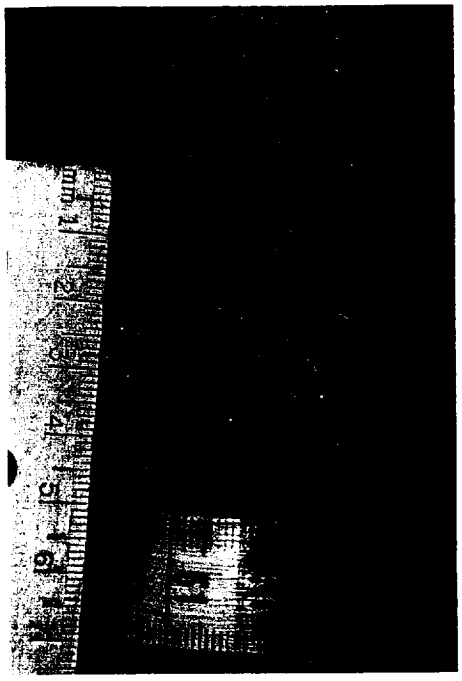


Figure 46. Complete scallop at Λ=40°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

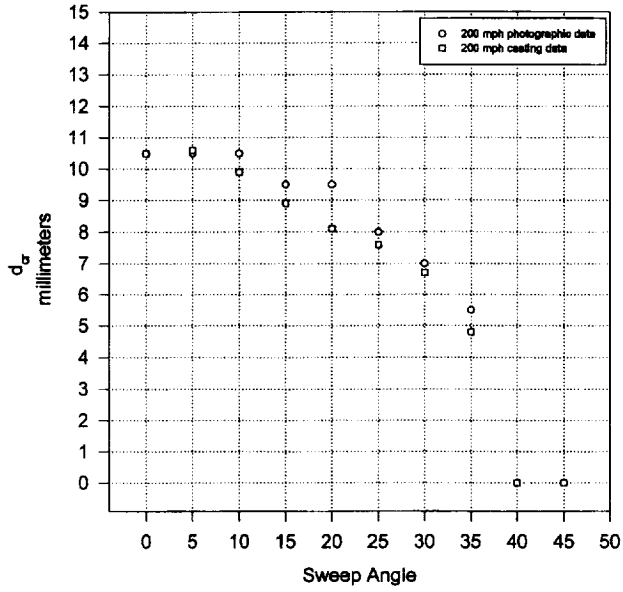


Figure 47. Change in critical distance with sweep angle at a velocity of 200 mph. Λ=0° to 45° at 5° increments, V=200 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min.

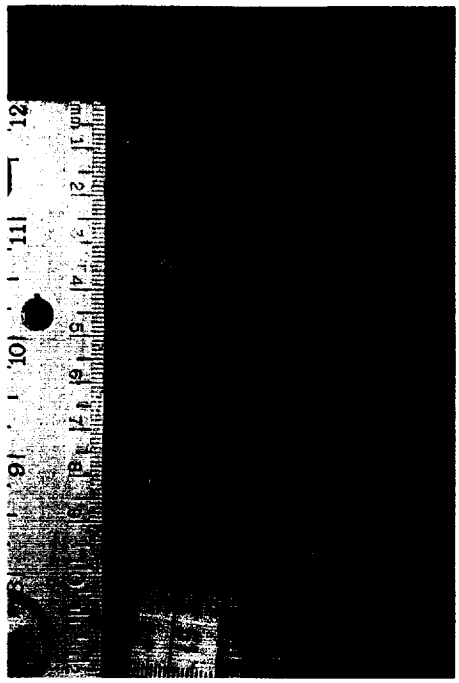


Figure 48. Front view of ice accretion showing the attachment line zone and the glaze ice feathers zone. Λ=0°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Scale of ruler is in centimeters, smallest division 1 millimeter.

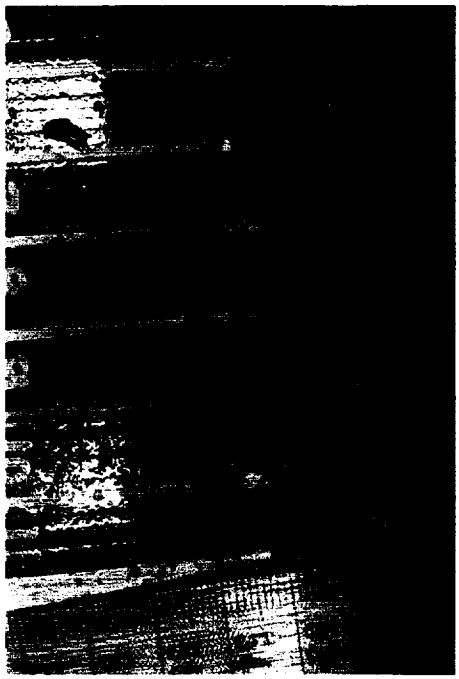


Figure 49. Side view of ice accretion showing the ice of the attachment line zone covering the feathers in the glaze ice feathers zone. Λ=0°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Scale of ruler is in centimeters, smallest division 1 millimeter.

Figure 50. Front view of ice accretion showing the ice of the attachment line zone covering the glaze ice feathers zone. Λ=10°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

Figure 51. Side view of ice accretion showing the ice of the attachment line zone completely covering the feathers in the glaze ice feathers zone. Λ=10°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

Figure 52. Front view of ice accretion showing scallop tips. Λ=35°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

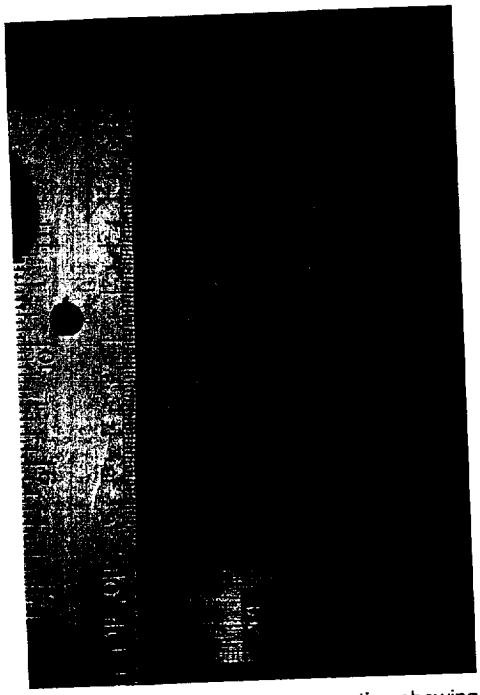


Figure 53. Front view of ice accretion showing complete scallops. Λ=40°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

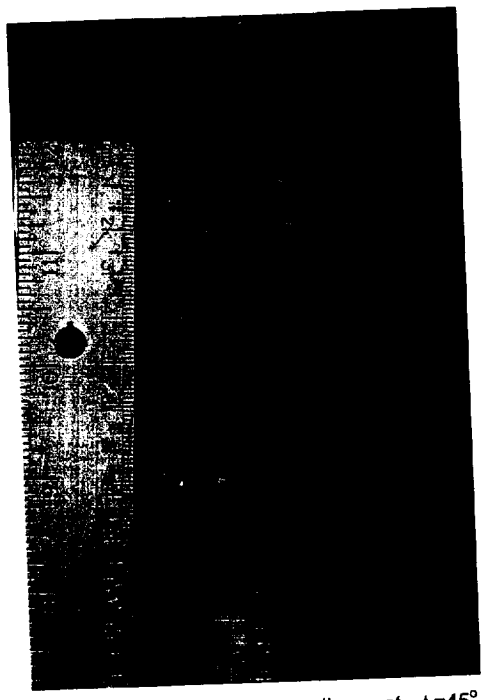


Figure 54. Complete scallops at Λ=45°, V=200 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, upper scale of ruler is in centimeters, smallest division 1 millimeter.

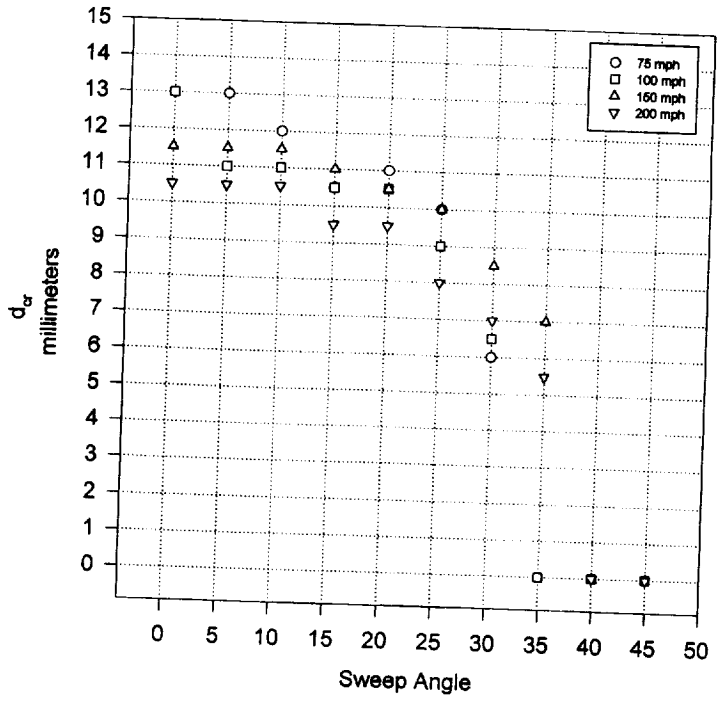


Figure 55. Change in critical distance with sweep angle for velocities of 75, 100, 150 and 200 mph. Λ=0° to 45° at 5° increments, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=5min.

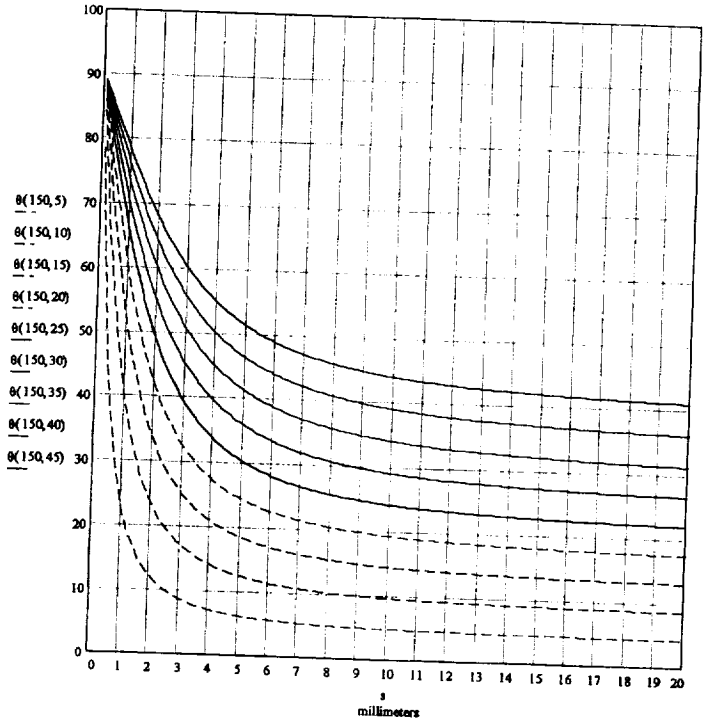


Figure 56. Angle θ in degrees, that the preferred direction of growth of the feathers makes with respect to the attachment line direction, versus the distance s from the attachment line, for sweep angles from 5° to 45° at 5° increments. The distance s is in millimeters.

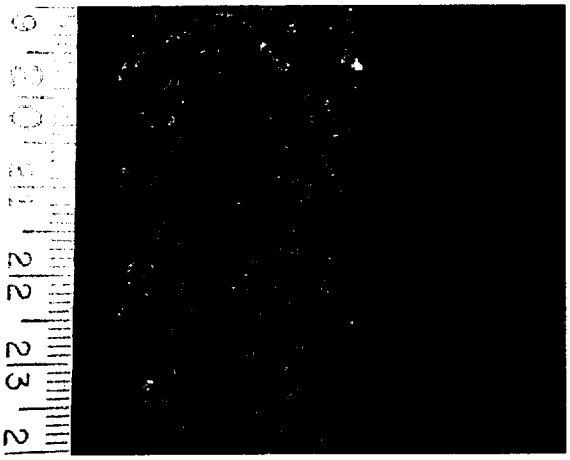


Figure 57. Front view of the beginning of the end cap showing the effect of the local sweep angle on the ice accretion. Λ=20°, V=150 mph, T=25°F, LWC=0.5g/m^3, MVD=20μm, τ=5min. Direction of flow is from bottom to top, scale of ruler is in centimeters, smallest division 1 millimeter.

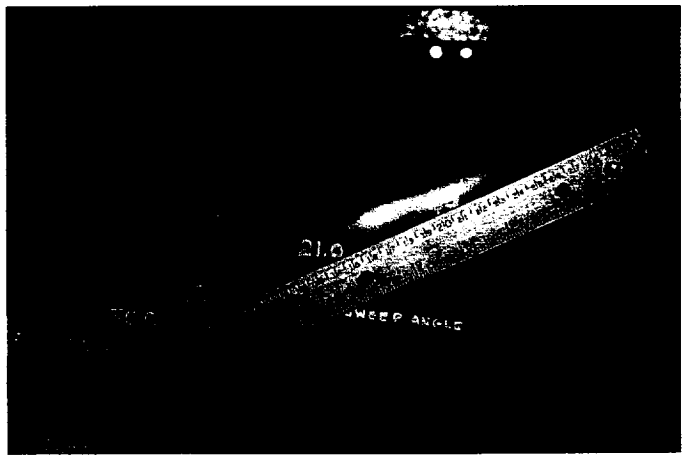


Figure 58. Side view of the end cap showing scallop formations along its length. Λ=0°, V=150 mph, T=25°F, LWC=0.75g/m^3, MVD=20μm, τ=5min. Direction of flow is from left to right, upper scale of ruler is in centimeters, smallest division 1 millimeter. The numbers on the grid painted on the airfoil are equal to 90° minus the local sweep angle at that location. The last red grid mark on the right corresponds to a local sweep angle of 72.5 degrees.

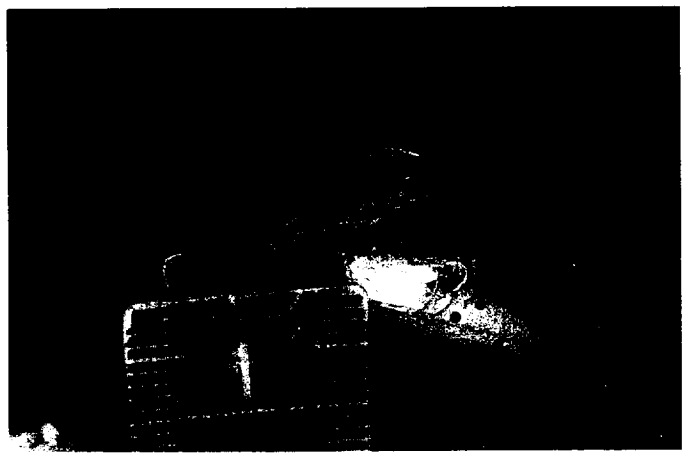


Figure 59. Side view of a single scallop at the end of the end cap. Λ=10°, V=75 mph, T=25°F, LWC=0.8g/m^3, MVD=20μm, τ=10min. Direction of flow is from right to left, scale of ruler is in centimeters, smallest division is 1 millimeter.

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13. ABSTRACT ***(Maximum 200 words)***

An experiment was conducted to study the effect of velocity and sweep angle on the critical distance in ice accretion formation on swept wings at glaze ice conditions. The critical distance is defined as the distance from the attachment line to the beginning of the zone where roughness elements develop into glaze ice feathers. Icing runs were performed on a NACA 0012 swept wing tip at velocities of 75, 100, 150, and 200 miles per hour. At each velocity and tunnel condition, the sweep angle was changed from 0° to 45° at 5° increments. Casting data, ice shape tracings, and close-up photographic data were obtained. The results showed that at given velocity and tunnel conditions, as the sweep angle is increased from 0° to 25°, the critical distance slowly decreases. As the sweep angle is increased past 25°, the critical distance starts decreasing more rapidly. For 75 and 100 mph it reaches a value of 0 millimeters at 35°. For 150 and 200 mph it reaches a value of 0 millimeters at 40°. On the ice accretion, as the sweep angle is increased from 0° to 25°, the extent of the attachment line zone slowly decreases. In the glaze ice feathers zone, the angle that the preferred direction of growth of the feathers makes with respect to the attachment line direction increases. But overall, the ice accretions remain similar to the 0° sweep angle case. As the sweep angle is increased above 25°, the extent of the attachment line zone decreases rapidly and complete scallops form at 35° sweep angle for 75 and 100 mph, and at 40° for 150 and 200 mph.

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